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Impact damage and failure response of aircraft composite structures

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ABSTRACT
Composite materials are increasingly being used in aerospace industry for primary structures such as engine cowlings or fuselage panels. Bird strike is a major threat which may lead to serious structural damage. The focus of current study is on the finite element modeling for composite structures and simulation of high velocity impact loads from soft body projectiles on composite structures with an explicit code AUTODYN. This paper investigates the methodology which can be utilized to certify an aircraft for bird strike using computational technique by first demonstrating the accuracy of the method for bird impact on rigid target modeling and then applies the developed model to a more complex problem. It is proposed that the results obtained from simulation can be utilized in the initial design stages as well as for certification of an aircraft for bird strike requirements as per federal regulations, since the physical testing of bird strike is expensive and time consuming.

Keywords: Aircraft composites, Bird strike, Damage, Failure, High Velocity, Impact, Lagrangian, SPH

1. INTRODUCTION

Engine cowlings on most airliners are manufactured from fibrous sandwich composites [1]. Cowling refers to the detachable panels with cutouts covering those areas into which access must be gained regularly, such as the engine and its accessories. It is designed to provide a smooth airflow over the nacelle and to protect the engine from damage. Engine cowlings reduce parasitic drag by reducing the surface area, having a smooth surface and thus leading to laminar flow, and having a nose cone shape, which prevents early flow separation. Bird strikes are a significant threat to flight safety, and have caused a number of accidents with human casualties. The number of major accidents involving civil aircraft is quite low and it has been estimated that there is only about 1 accident resulting in human death in one billion (10^9) flying hours. The majority of bird strikes (65%) cause little damage to the aircraft; however the collision is usually fatal to the bird(s) involved. Bird strikes happen most often during takeoff or landing, or during low altitude flight.

The increasing number of bird-plane high velocity impacts gives rise to new CAE methods to address aircraft safety. Since bird strike is more challenging and may lead or cause to serious aircraft crash [2]. As per certification regulations [3], an aircraft must demonstrate its ability to land safely after being struck by a bird anywhere on the structure, at normal operating speeds. The standards ensure that aircraft designers conduct extensive bird strike testing and analysis of facing components: engine cowling, horizontal tail plane, end plate, vertical fin etc. before the aircraft is certified for flight [4]. Consequently, the aviation authorities require that all forward facing components need to prove a certain level of bird strike resistance in certification tests before they are allowed for operational use. A bird strike event is characterized by loads of high intensity and short duration. The duration of the forcing function for bird impact loading is typically in the range of milli-seconds. During impact, both the airplane structure (target) and the bird (projectile) undergo high, inelastic strain rates and large deformations. The certification clauses demand that the aircraft be able to successfully land after the leading edges being struck with a standard bird at cruise velocity of the aircraft for a given altitude. It is proposed that the results obtained from simulation can be utilized in the initial design stages as well as for certification of an aircraft for bird strike requirements as per federal regulations, since the physical testing of bird strike is expensive and time consuming. European Aviation Safety Agency (EASA) and Federal Aviation administration (FAA) airworthiness regulations require that an aircraft be designed to successfully complete a flight after an impact with a standard-size bird. These standards/regulations ensure that aircraft designers bird-proof the forward-facing components of the aircraft – such as windshields and windows, aircraft engines and leading edge structures – before the aircraft is certified for flight.

The current paper presents the accuracy of numerical bird models the purpose of this work is to develop reliable improved design tool for passengers protection when an aircraft undergoes soft body impact, such a bird or high velocity debris impact while decreasing the time and costs involved in the certification process. The aircraft must be designed to ensure capability of continued safe flight and landing or safe landing after impact with a 2.2-lb (1.0 kg) bird when the velocity of the aircraft (relative to the bird along the flight path of the rotorcraft) is equal to VNE or VH (whichever is the lesser) at altitudes up to 8,000 feet[5]. Compliance must be shown by tests or by analysis based on tests carried out on sufficiently representative structures of similar design. Cowling is one of important component of an aircraft which can be affected by bird strike.

2. BIRD MODELING TECHNIQUES

Dr. James Wilbeck [6] was one of the first researchers to investigate the experimental behavior of a bird under impact. Substitutes like gelatin, beef, RTV rubber, and neoprene have been tried and compared against data from a chicken projectile. The validity of the substitute is assessed by comparing the pressure reading at the center of a flat rigid plate between substitutes impacting at the same velocity. Experiments showed that the most suitable substitute material is gelatin in which air is mixed to obtain a final porosity of 10% and an average density of 950 kg/m^3. Under impact, the gelatin adopts the same behavior as water, and its low strength enables it to keep its shape until the impact, making it easier to handle and launch than actual water. The substitute bird was developed using two main modeling methods are currently available are considered in the analysis [7]. Currently, highly detailed models of the bird and the target structure can be built using a variety of spatial discretization modeling approaches; and the simulations may be performed using various solution strategies, including a Lagrangian, and Smooth Particle Hydrodynamics (SPH) approaches. The simulation technique can be chosen from these two methods. At first, a lagrangian approach is adopted with trial and error procedure and then extended to SPH method.

A. Lagrangian Bird Model

The Lagrangian technique is mainly used for solving problems related to solid mechanics. The Lagrangian modeling method divides a volume into a large number of small geometries called elements. Because those geometries are simple in shape, it is possible to know the state of the solid through the simulation by using mathematical relations. In this technique, the numerical mesh is attached to the structure. The structure itself

is divided into discrete finite elements, forming the finite element mesh. Since the mesh of the Lagrangian solver forms an integral part of the structure, the deformations and distortions of the structure are reflected in the mesh. It has been reported that element erosion at the contact-impact interface introduces additional complications [8]. Adaptive remeshing, or adaptivity, involves re-meshing the region of severe mesh tangling. This additional step, in addition to increasing the solution time, involves the complex remapping of all the solution variables from the original distorted mesh to the new regular mesh. The interaction with the target is controlled by node-to-surface contact algorithm between the bird and target [9] in order to overcome large distortions. Deleting elements that exceed a pre-imposed plastic strain threshold value resolves both negative volumes and time step decrement issues.

B. Smooth Particle Hydrodynamics (SPH) Bird Model

Smoothed-particle hydrodynamics (SPH) is a computational method used for simulating fluid flows. It was developed by Gingold and Monaghan [6] and Lucy initially for astrophysical problems. Initially this method was used to simulate astrophysical phenomenon, but recently it has been used to resolve other physics problems in continuum mechanics, crash simulations, brittle and ductile fracture in solids [10 - 12]. Due to the absence of a grid, this method allows solving many problems that are hardly reproducible in other classical methods discarding the problem of large mesh deformations or tangling: due to the absence of a mesh, problems with irregular geometry can be solved. The smoothed-particle hydrodynamics (SPH) method works by dividing the fluid into a set of discrete elements, referred to as particles. In this formulation, the fluid is represented as a set of moving particles, each one representing an interpolation point, where all the fluid properties are known [13]. The SPH method presents some disadvantages: first of all is very computationally demanding, both in memory and in CPU time. This can be overcome using a parallel analysis with more than one CPU; another disadvantage is that particles may penetrate the boundaries and causing loss of smoothness and accuracy for big deformations. To validate the accurate bird model, it is impacted on a rigid plate and is compared with experimental data from literature [17]. Then the accurate bird model is impacted on engine cowling structure. SPH is a competitive approach compared to finite elements (FE) and is increasingly being used in some fast-transient dynamics problems. Each of these numerical techniques has relative advantages and disadvantages.

3. DESIGN METHODOLOGY

The bird modeling methods are described in the previous section. Regardless of the modeling method the material usually employed to model the bird is elastic-plastic hydrodynamic with the polynomial equation of state (EOS) of equation. The material of the bird considered is water with an average density of 938.5 kg/m^3 by assuming 10% porosity. All the models the bird was represented by an idealized geometry and the material model were defined by an equation-of-state (EOS) to describe the pressure-density relationship in the bird medium. One of the main problems in the bird strike analysis is choosing of a shape, material properties and a simulation approach for an object, which model the bird. Budgey [14] and Stoll [15] have compared the finite element results obtained by using different shapes of birds such as a straight-end cylinder or an ellipsoid and have agreed that the geometry of Figure 2 is more adequate. McCallum [16] modeled a more detailed geometry that includes neck, wing and body. However, for certification purposes, the dead birds are compacted into a cylinder and launched as such, making the bird shaped as its container. Since the purpose of the simulations is to correlate to the certification, it is more appropriate to use the cylindrical shape. Tests also showed that the geometry of the projectile is of importance. The most suitable shape for the projectile is a cylinder with hemispherical ends with a length to diameter ratio equal to 2, as illustrated by Figure 1.

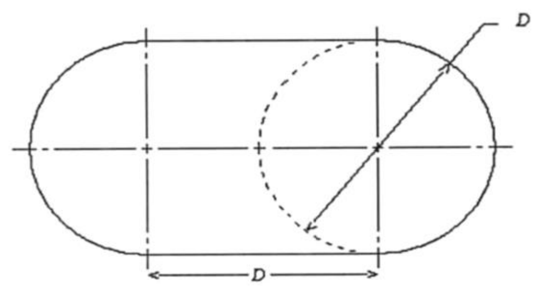


Figure 1 Bird geometry

Volume of the bird is given by:

$$Volume = \frac{\pi d^3}{6} + \frac{\pi d^3}{4} = \frac{5\pi d^3}{12}$$

For a material such as water which exhibits the linear Hugoniot relation between shock velocity v_p and particle velocity v_s.

$$V_s = c_0 + kv_p$$

The bird strike has been divided into two stages: the initial shock and the steady flow [6]. The pressure of the initial shock (Hugoniot pressure) is given by equation (1); the pressure of the steady flow (stagnation pressure) is calculated according to Bernoulli and is given by equation (2):

$$P_{sh} = \rho_0 \, v_{sh} \, v_{im} \quad (1)$$

Equation (2) gives the stagnation pressure for an incompressible fluid;

$$P_{stag} = \frac{1}{2}\,\rho_0\, v_{1m}^2 \quad (2)$$

These two pressures are important because the Hugoniot pressure gives the maximum possible value for the impact and the stagnation pressure gives the expected reading when the flow stabilizes.

Experimental diagrams are defined in terms of shock pressure (P_{sh}), and stagnation pressure (P_{Stag}), pressures vs. impact velocity and normalized pressure (P_{ad}) vs. normalized timec(t_{ad}) for the impact velocity of 116m/s. Normalized pressure and time are expressed by relations [17].

$$p_{ad} = \frac{p}{{}^{1}\!/_{2}\rho U_0^2}\,;\, t_{ad} = \frac{TU_0}{L}$$

One of the most commonly used for bird impacts is a polynomial of degree 3 [6] defined as below.

$$P = C_o + C_1\mu + C_2\mu^2 + C_3\mu^3;$$

Where μ is given by $\mu = \rho/\rho_0 - 1$ and represents the change in density during the impact. This polynomial equation of state for the bird model corresponds to a hydrodynamic, isotropic and non viscous constitutive law. The coefficients are given by expressions based on the initial density ρ_0, the speed of sound in water and an experimental constant k [6].

The expressions are:

C_o = initial equilibrium pressure, negligible;

$C_1 = \rho_0 c_o^2$;

$C_2 = (2k-1)\, C_1$;

$C_3 = (k-1)\,(3k-1)\, C_1$

Where ρ_0 is the initial density, c_0 = 1482.9m/s is the speed of sound in water, *k=2* is an arbitrary parameter determined by Wilbeck's tests and C_1 is the bulk modulus of the impactor material. The coefficients are given by expressions based on the initial density ρ_0, the speed of sound in water and an experimental constant *k*.

4. VERIFICATION FOR ACCURATE BIRD MODEL

A. Problem statement

The reliability of the various parameters discussed are first validated with known solution[17] by simulating a 1.82kg(4lb) bird and is impacted on a 0.7×0.7×0.01 m square rigid plate (fig 2) with an impact velocity of 116m/s. The material properties of Aluminum plate and the design parameters of bird are given in Table 1 and Table 2 respectively.

Table 1 Properties of Aluminum plate

Mass Density	2700 kg/m^3
Young's Modulus (E)	70e9 Pa
Poisson's Ratio	0.3

Table 2 Bird Parameters

Mass	1.82 kg (4 lb)
Geometry	Cylinder with hemispherical ends
Density	938.5 kg/m^3
Material	Elastic-plastic hydrodynamic Fluid (Water)

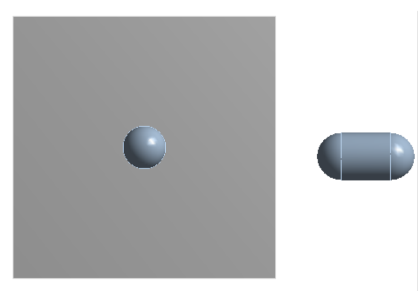


Figure 2 0.7×0.7×0.01 m square rigid plate with bird

B. Discussion of results

In order to establish a range to validity of the bird model, the benchmark problem is chosen and comparison is made with the available experimental data. In the present study the Lagrangian and SPH bird model are considered to evaluate the accuracy of the analysis technique.

C. Lagrangian Bird Model

The pressure at the center of impact for the Lagrangian mesh is plotted. The shock pressure reached is of about 7.1, which is much lower than the expected value of 12.0. Lagrangian elements for the bird proved unsatisfactory, because the bird behaves hydro-dynamically, undergoing severe deformations upon impact. The consequent severe distortions in the Lagrangian elements of the bird resulted in several difficulties, such as a necessity for an extremely small time step size and negative element volumes. While increasing the density of the mesh one might be able to increase the quality of the pressure results, more mass would be lost, hence never reaching an acceptable result. The distortions sequence of the bird model impacting the rigid plate, are shown in Figure 3.

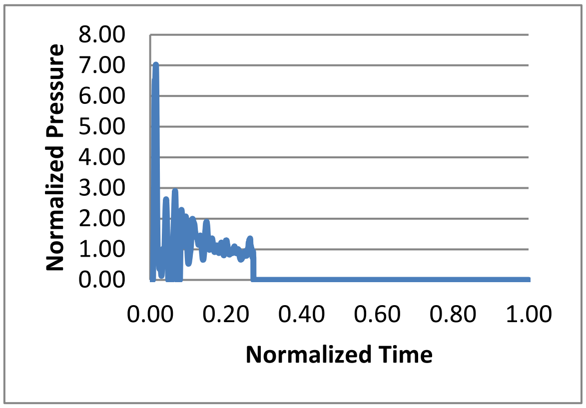


Figure 3 Normalized pressure distortions

D. Smooth Particle Hydrodynamics (SPH) Bird Model

It is a mesh-free Lagrangian method. The smoothed-particle hydrodynamics (SPH) method works by dividing the fluid into a set of discrete elements, referred to as particles. Increasing the number of particles clearly has an influence on the pressure results. The SPH bird model includes 15163 evenly distributed nodes. The pressure at the center of impact for the SPH bird model is plotted. The shock pressure reached is of about 10.7, which is lower than the expected value of 12.0. But it is the best approximate method for a bird strike when compared to a lagrangian method. The distortions sequence of the bird model impacting the rigid plate, are shown in Figure 4.

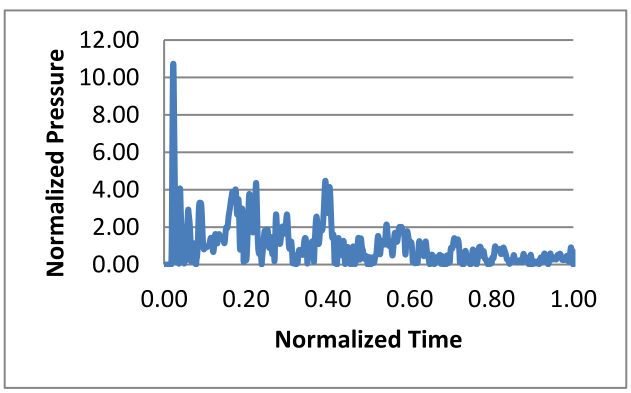


Figure 4 Normalized pressure distortions

From the literature, Hugoniot pressure is expected to have a maximal value of about 60 MPa and a stagnation pressure of 5 MPa, giving normalized values of 12 and 1.0, respectively. Finally, the duration of the impact is of 1.96 ms. Analytical results of Hugoniot pressure and stagnation are compared with the experimental data [17] as shown in table 3.

Table 3 Comparision of Experimental and Theoretical results with Numerical results

	Hugnoit Pressure	Stagnation Pressure
Experimental	60	5
Theoretical	100	6
Lagrangian Bird model	49	7
SPH Bird model	65	6

Now, the best of each method are compared together. The pressure curves of the selected solutions are shown. It is good to notice that the shock pressures are reached simultaneously and that the stagnation pressure is reached at about a second of the simulations. Plotting the two different methods together also highlight the fact that the Lagrangian results are much lower than the results of the SPH method. They are also spurious, which can be attributed to the continual flow of elements being deleted. As for the SPH results, they yield a shock pressure which is almost the same. The SPH pressure is more spurious than the lagrangian one, which is due to the method itself when each individual particle hits the target. The next section explains explicit dynamic analysis of practically important problem of cowling.

5. EXPLICIT DYNAMIC ANALYSIS OF COWLING STRUCTURE

In the current paper an attempt has been made to consider the state of art composite modeling for damage evaluation under high velocity impact loading. A CAD model of cowling was generated in ProE. So, finite element model was developed using Ansys composite prepost for analysis. Explicit dynamic analysis is carried by using AUTODYN for validated SPH bird model to assess the accuracy and demonstrate the proof of a complex situation.

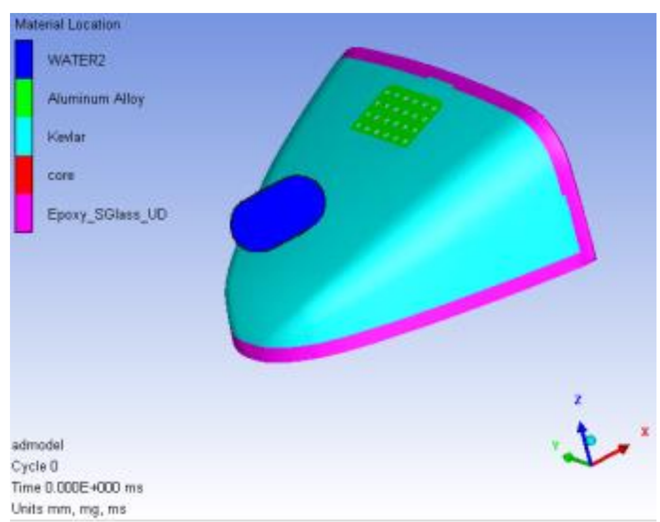


Figure 5 Cowling structure geometry

The geometry of the cowling structure considered for the analysis is shown in figure 5. It consists of composite face-sheets on inner and outer sides of nomex core. The prepregs used in composite face-sheets are Kevlar epoxy and glass epoxy with specified lamination scheme.

A. FE model of cowling

The FE model developed for highly non-linear explicit dynamic analysis is shown in figure 6. The numerical model includes a composite structure target modeled with 19428 shell elements and the bird modeled with about 8000 particles.

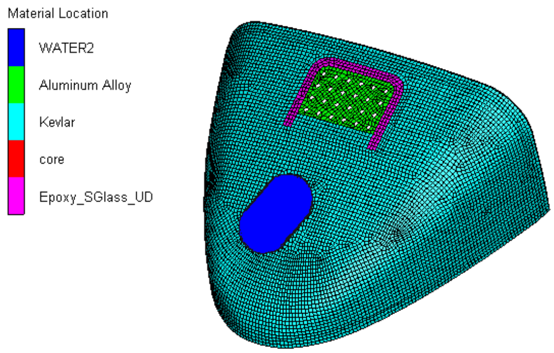


Figure 6 FE model of cowling structure

Finally it is also of interest to know how much energy can be impacted by the bird to the cowling structure.

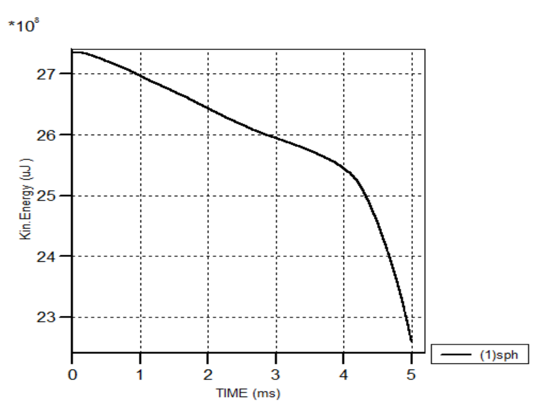


Figure 7 Plot of Kinetic Energy with time

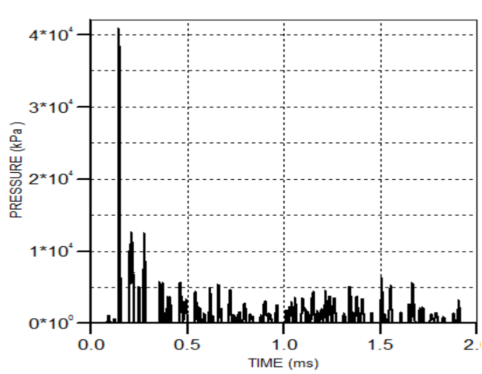


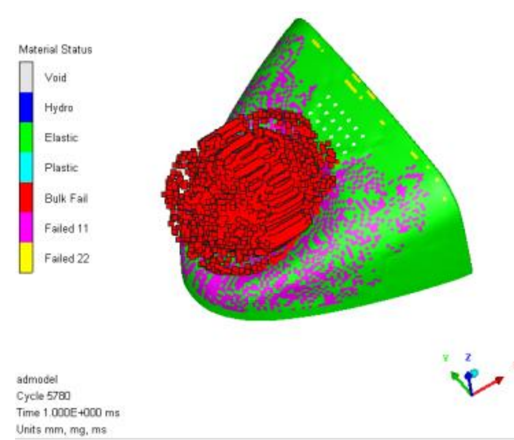
Figure 8 Pressure vs. Time

B. Loads and boundary conditions

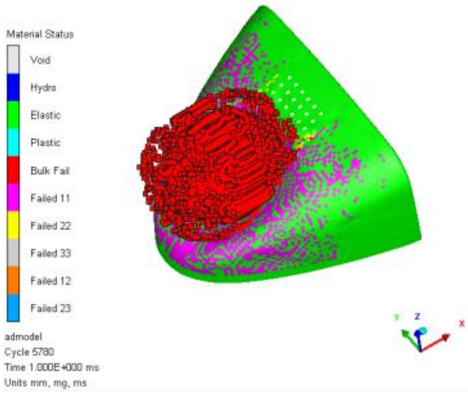
In order to carried out bird strike simulation under impact loading the cowling was constrained all around edges. A 1kg bird travelling at a velocity of 85 m/s impacts the facing of the cowling. Automatic nodes to surface contact control the interaction between the projectile and target. An elastic material model is used for the cowling structure and an elastic-plastic-hydrodynamic material model with a polynomial equation of state is used to model the bird. The physical properties of the bird are given using the international system of units and the simulation ran for 5ms. The deign parameters of the bird are taken from table 3. During the numerical analysis, a 1 kg bird substitute impacted on a cowling structure at a velocity of 85m/s. Figure 7 shows the kinetic energy dissipated by the bird at different time intervals during impact. Figure 8 shows the variation in shock pressure and steady flow pressure distribution for a bird projectile. There is a raise of pressure at the impact and then the pressure stabilizes around its stagnation value at around one-third of the impact.

6. RESULTS DISCUSSION

The SPH method, implemented in the explicit element code AUTODYN, is used to model the bird in an impact on the cowling structure. So damage pattern with time intervals is shown in the Fig. 9 concerning the deformed shape of the bird at the structure. It is observed that the use of FE model is feasible only in the early stages of impact. When the bird is characterized by large distortions can cause a decreasing of the time step an unacceptable low value for the calculations to continue because in an explicit finite element analysis, the time step is determined by the smallest element dimension. The time interval used to calculate the damage behavior from the simulation is approximately equal to the squash time.



Layer-1, cycle-5780, time-1.0ms



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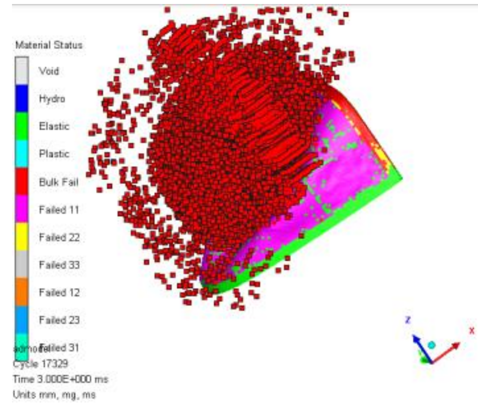
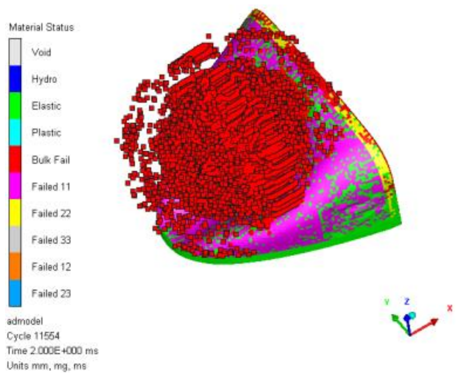
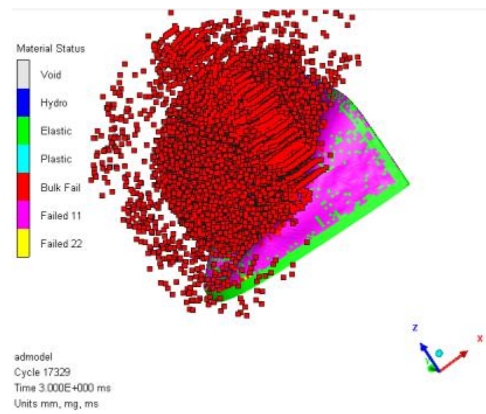


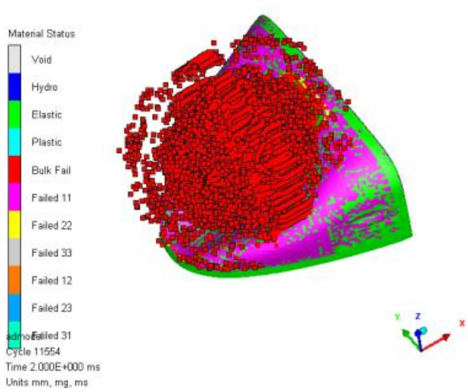
Layer-1, cycle-17329, time-3.0ms



Layer-1, cycle-11554, time-2.0ms



Layer-9, cycle-17329, time-3.0ms



Layer-9, cycle-11554, time-2.0ms

Figure 9 Layer wise analysis and Damage behavior of cowling

7. CONCLUSIONS

In the present work a highly non linear explicit dynamic analysis has been carried out on the composite structure under high velocity loading. Penetration of composite structures by a soft body impactor has been investigated and simulations were performed to assist in the development of the modeling requirements for simulating bird impact. SPH method results from this study to successfully develop a finite element model of a substitute bird that can accurately predict the loads impacted on the target. So given the success of SPH method in the present work, it should be used in subsequent work involving more complex fluid solid interaction as in aircraft ditching simulation.

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